

# A Search For CP Violation in Hyperon Decays by the HyperCP Experiment at Fermilab

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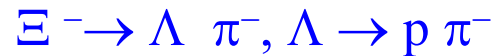
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# Nonleptonic Decays of Hyperons

- The parity-violating weak decays we are interested in are:



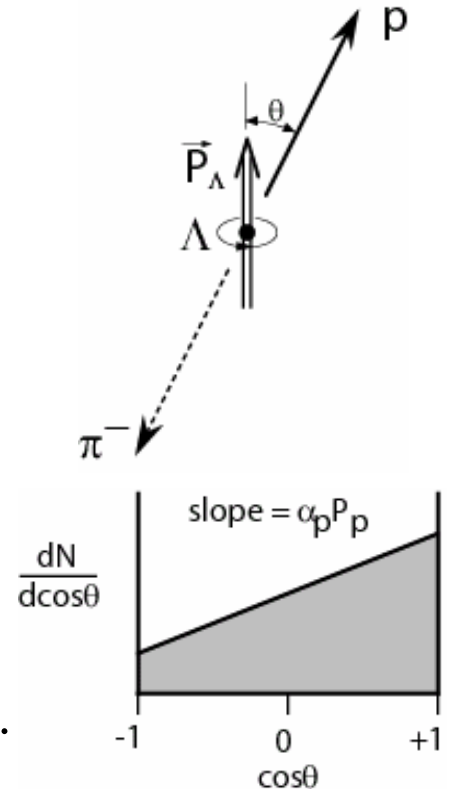
- The  $\Lambda$  and  $p$  have an angular decay distribution that takes the following form:

$$\frac{dN}{d \cos \theta} = \frac{N_0}{2} (1 + \alpha_p \vec{P}_\Lambda \cos \theta)$$

- Where the  $\alpha$  decay parameter for the  $\Lambda$  and  $\Xi$  is:

$$\alpha_{\Lambda, \Xi} = \frac{2 \operatorname{Re}(S^* P)}{|S|^2 + |P|^2}$$

- $S$  and  $P$  are the angular momentum wave amplitudes.
- The  $\alpha_\Xi$  and  $\alpha_\Lambda$  are **large** and are a measure of parity violation.



# $CP$ Violation in Hyperon Decays

- If  $CP$  is conserved then:

$$\alpha_{\Lambda} = -\alpha_{\bar{\Lambda}} \quad \text{and} \quad \alpha_{\Xi} = -\alpha_{\bar{\Xi}}$$

- The  $CP$ -asymmetry parameters are defined as:

$$A_{\Lambda} = \frac{\alpha_{\Lambda} + \alpha_{\bar{\Lambda}}}{\alpha_{\Lambda} - \alpha_{\bar{\Lambda}}} \quad A_{\Xi} = \frac{\alpha_{\Xi} + \alpha_{\bar{\Xi}}}{\alpha_{\Xi} - \alpha_{\bar{\Xi}}}$$

- These parameters are related to the strong- and weak-phase differences:

$$A_{\Lambda} \cong -\tan(\overbrace{\delta_1^P - \delta_1^S}^{\text{strong}}) \sin(\overbrace{\phi_1^P - \phi_1^S}^{\text{weak}})$$

$$A_{\Xi} \cong -\tan(\delta_3^P - \delta_3^S) \sin(\phi_1^P - \phi_1^S)$$

- HyperCP* has measured the  $\Lambda$ - $\pi$  strong phase shift difference to be  $4.6 \pm 1.4 \pm 1.2^\circ$ .
- But we need to know the **polarization** to measure the  $\alpha$  parameter

# How does *HyperCP* produce $\Lambda$ s with a known Polarization?

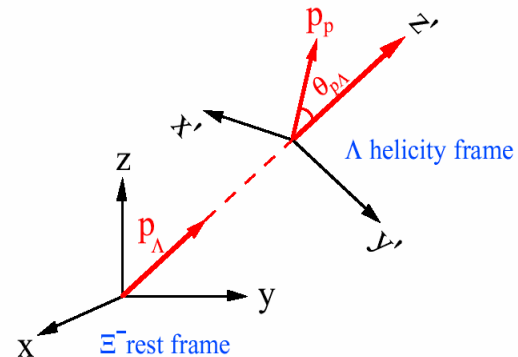
- The experimental approach is to use **unpolarized**  $\Xi^-$  decays. The **unpolarized**  $\Xi^-$  are produced by targeting the beam at  $0^\circ$  with respect to the collimator.
- The polarization of a daughter particle from an unpolarized parent is known to be:

$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda$$

- This means that the angular decay distribution of the  $\Lambda$  can now be described by:

$$\frac{dN_p}{d\cos\theta_{p\Lambda}} = \frac{N_0}{2} (1 + \alpha_\Lambda \alpha_\Xi \cos\theta_{p\Lambda})$$

$$A_{\Xi\Lambda} = \frac{\alpha_\Xi \alpha_\Lambda - \alpha_{\Xi^-} \alpha_{\bar{\Lambda}}}{\alpha_\Xi \alpha_\Lambda + \alpha_{\Xi^-} \alpha_{\bar{\Lambda}}} \approx A_{\Xi^-} + A_\Lambda$$



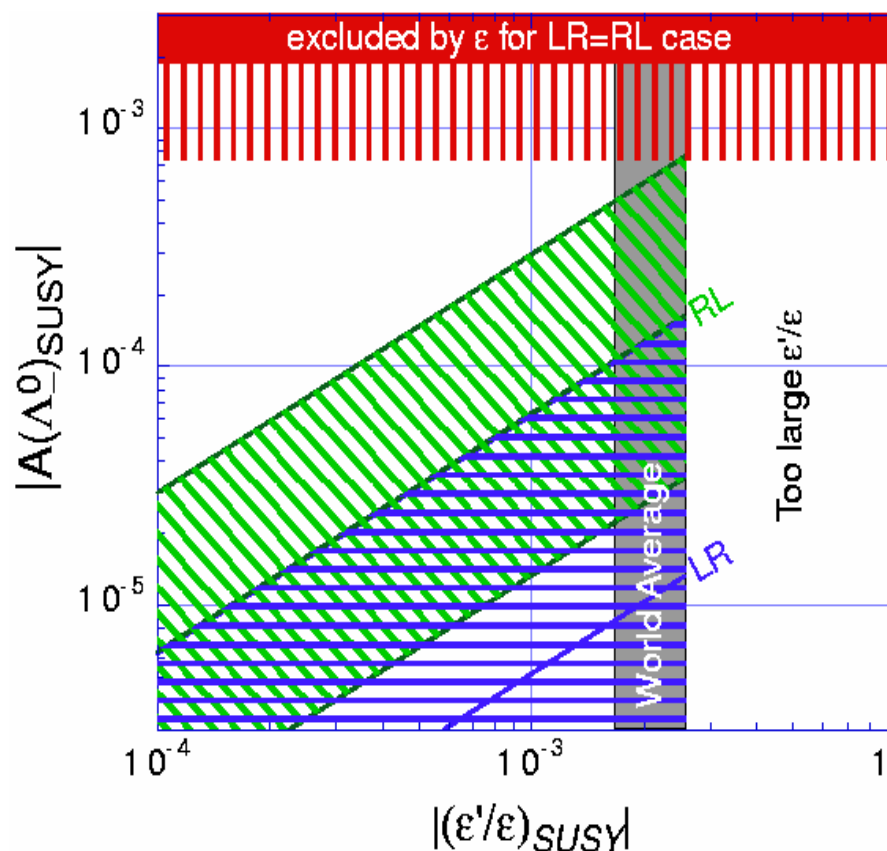
# How is this different from $\varepsilon'$ ?

- $A_{\Xi\Lambda}$ 
  - Interference arises from a  $CP$  violating phase difference in the S and P wave amplitudes
  - Combines both Parity violating and **conserving** amplitudes
- $\varepsilon'/\varepsilon$ 
  - Interference arises from a  $CP$  violating phase in the  **$I = 0$  and  $I = 2$**  amplitudes
  - Consists of **only** Parity violating amplitudes

*“Our results suggest that this measurement is complementary to the measurement of  $\varepsilon'/\varepsilon$ , in that it probes potential sources of  $CP$  violation at a level that has not been probed by Kaon experiments” (He and Valencia)*

# Theoretical Predictions

- Standard Model predicts that  $A_\Lambda$  is from  $-3 \times 10^{-5}$  to  $4 \times 10^{-5}$  and  $A_\Xi$  is from  $-2 \times 10^{-5}$  to  $1 \times 10^{-5}$  (Tandean and Valencia).
- Some SUSY models predict  $A_\Lambda$  values up to  $1.9 \times 10^{-3}$  (He et al.).
- Most models predict  $A_\Xi$  to be **smaller** than  $A_\Lambda$ .
- *HyperCP* will measure  $A_{\Xi\Lambda}$  at the level of  $\approx 2.0 \times 10^{-4}$ , thus a positive result would be a signal for new physics



# Experimental Results

Experiment	Mode	$A_{\Lambda}$
R608 at ISR	$p\bar{p} \rightarrow \Lambda X, p\bar{p} \rightarrow \bar{\Lambda} X$	$-0.02 \pm 0.14$
DM2 at Orsay	$e^+e^- \rightarrow J/\Psi \rightarrow \bar{\Lambda}\Lambda$	$0.01 \pm 0.10$
PS185 at LEAR	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	$-0.013 \pm 0.022$

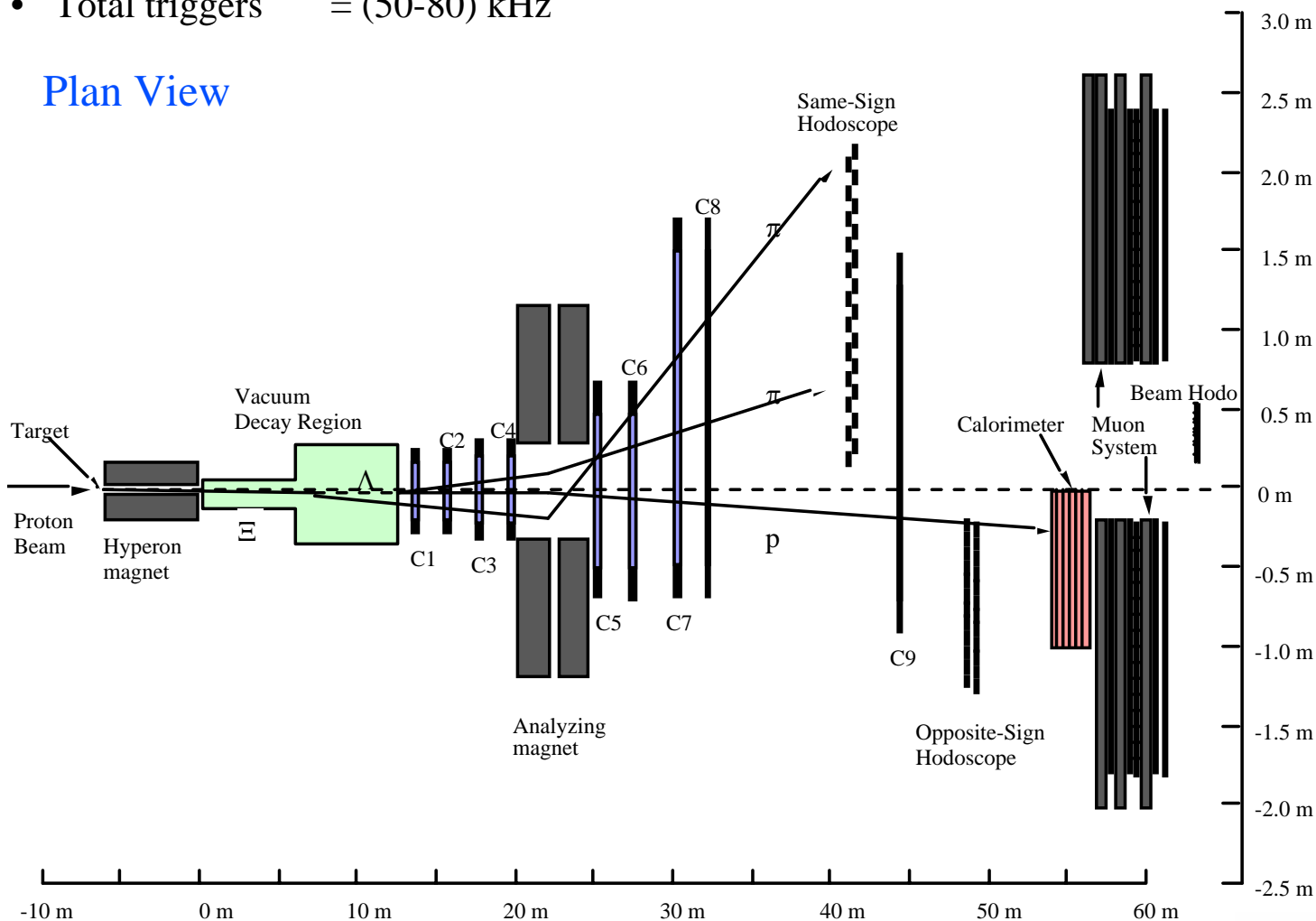
Experiment	Mode	$A_{\Xi\Lambda}$
FNAL E756	$\Xi \rightarrow \Lambda\pi, \Lambda \rightarrow p\pi$	$0.012 \pm 0.014$

- *HyperCP* will measure  $A_{\Xi\Lambda}$  with unpolarized  $\Xi^-$  and  $\Xi^+$  hyperons produced by 800 GeV protons to a precision two orders of magnitude better than any previous experiment.

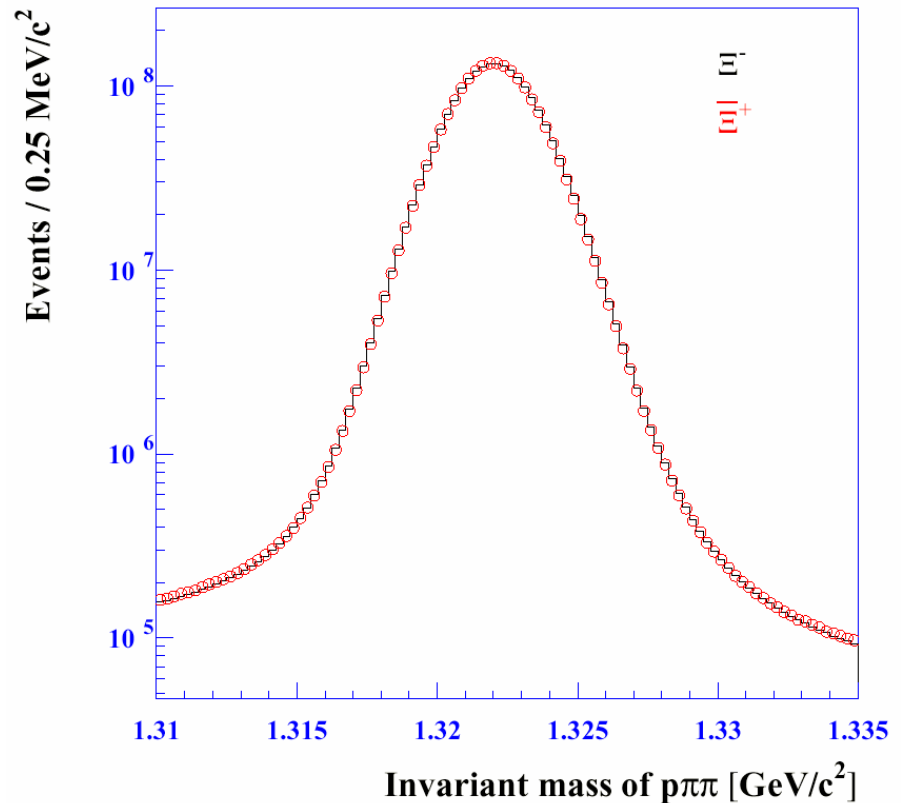
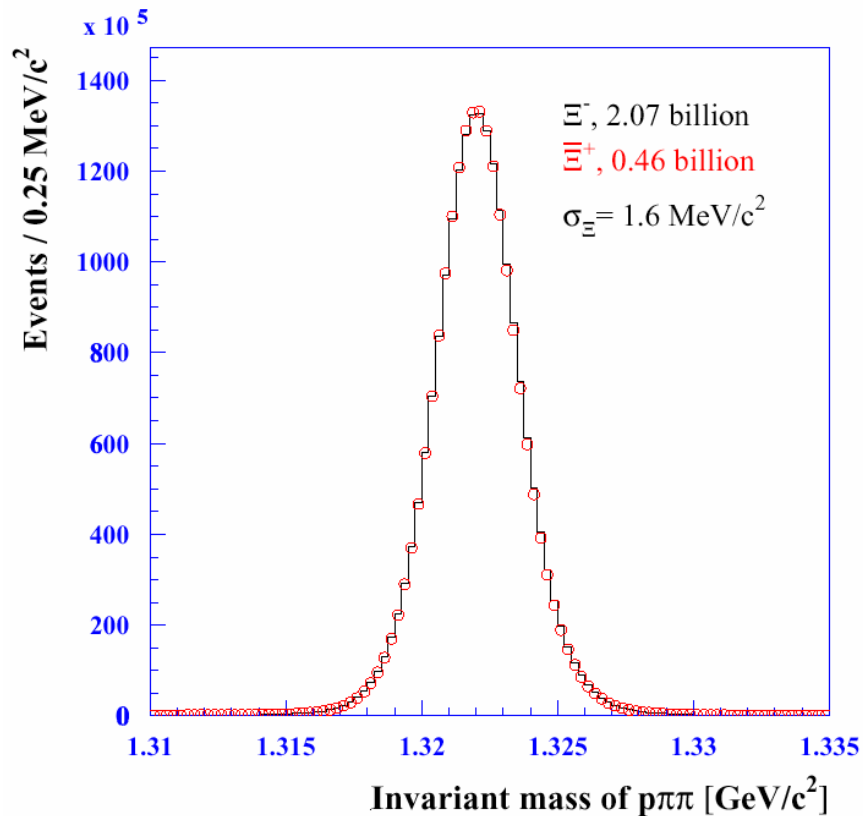
# The *HyperCP* Spectrometer

- Protons on target = (7-8) GHz
- Sec. beam inten. = (10-15) MHz
- Total triggers = (50-80) kHz

## Plan View

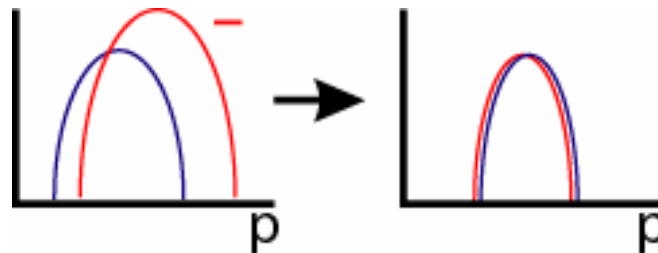
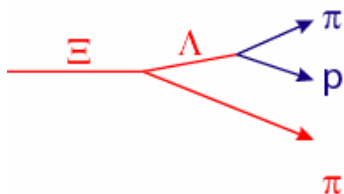


# Statistics of the 1997 and 1999 Runs



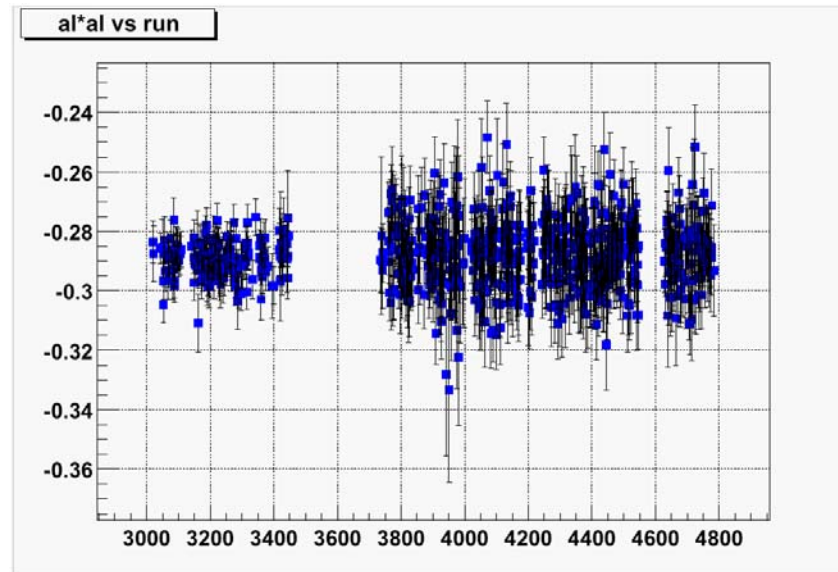
# Two analysis methods

- Using two methods allows us to **cross check** our result
- **HMC Method** – Uses real events, replacing the proton and pion by generating 10 new unpolarized decays
- **Advantage**: well-tested and understood method
- **Disadvantage**: Monte Carlo requires detailed simulation of trigger and detector response .
- **Weighting method**- Force two samples to have similar production momentum and spatial distributions
- **Advantage**: No Monte Carlo measurement of acceptance needed
- **Disadvantage**: no absolute measure of  $\alpha_{\Lambda}\alpha_{\Xi}$ .



# HMC measurement of $\alpha_{\Xi}\alpha_{\Lambda}$ and $A_{\Xi\Lambda}$

- Data sample: **randomly selected**  $\Xi$  events during data reduction; about  $15 \times 10^6$   $\Xi^-$  and  $30 \times 10^6$   $\Xi^+$  events.
- Average  $\alpha_{\Xi}\alpha_{\Lambda} = -0.2880 \pm 0.0004(\text{stat})$ , in agreement with PDG value with  $\chi^2 = 26/19$  dof.



- **Preliminary result:**  $A_{\Xi\Lambda} = [-7 \pm 12(\text{stat}) \pm 6.2(\text{sys})] \times 10^{-4}$

# Weighting Method:

## Correcting for the Acceptance Difference

- For a **non-perfect** detector one must add an acceptance term:
- If one takes a **ratio** of the two distributions the acceptance cancels:
- The difference is:
- The fitting function used was:

$$\frac{dP}{d\cos\theta} = \frac{1}{2} A(\cos\theta) (1 + \alpha_{\Lambda} \alpha_{\Xi} \cos\theta)$$

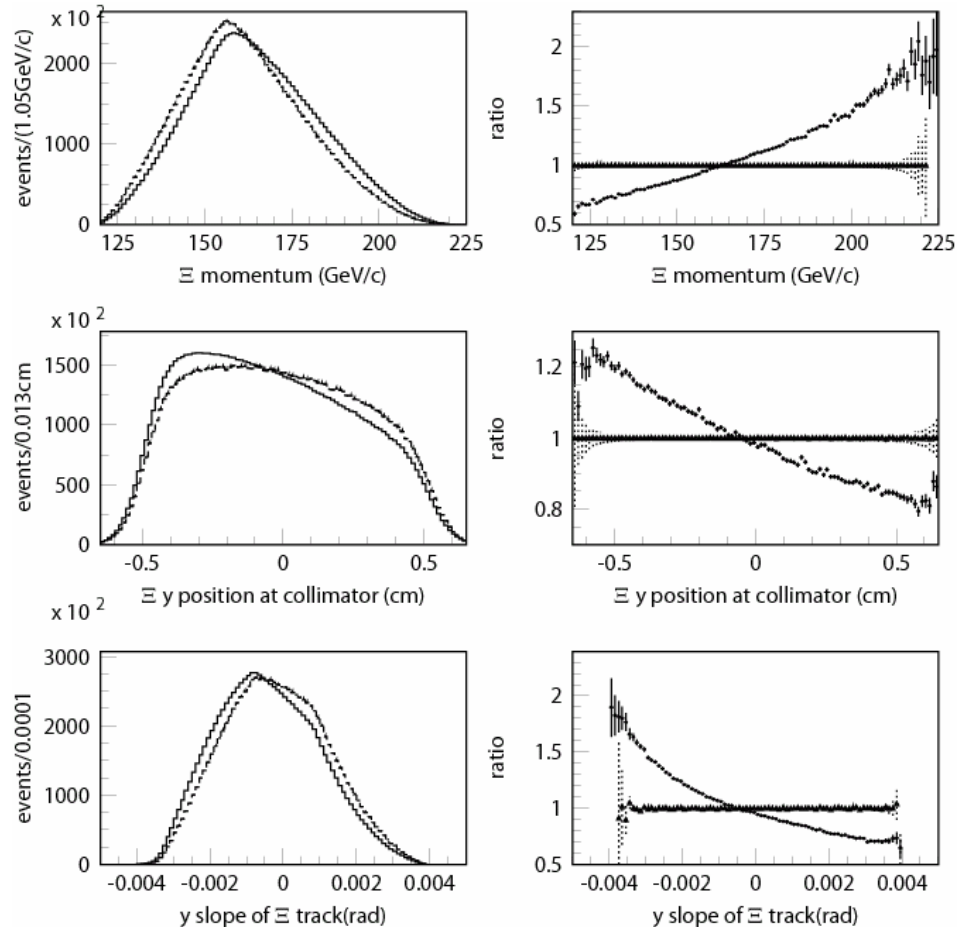
$$Ratio = \phi \frac{(1 + (\alpha_{\Lambda} \alpha_{\Xi})_- \cos\theta)}{(1 + (\alpha_{\Lambda} \alpha_{\Xi})_+ \cos\theta)}$$

$$\delta = (\alpha_{\Lambda} \alpha_{\Xi})_- - (\alpha_{\Lambda} \alpha_{\Xi})_+$$

$$Ratio = \phi \frac{(1 + (\alpha_{\Lambda} \alpha_{\Xi})_- \cos\theta)}{(1 + ((\alpha_{\Lambda} \alpha_{\Xi})_- - \delta) \cos\theta)}$$

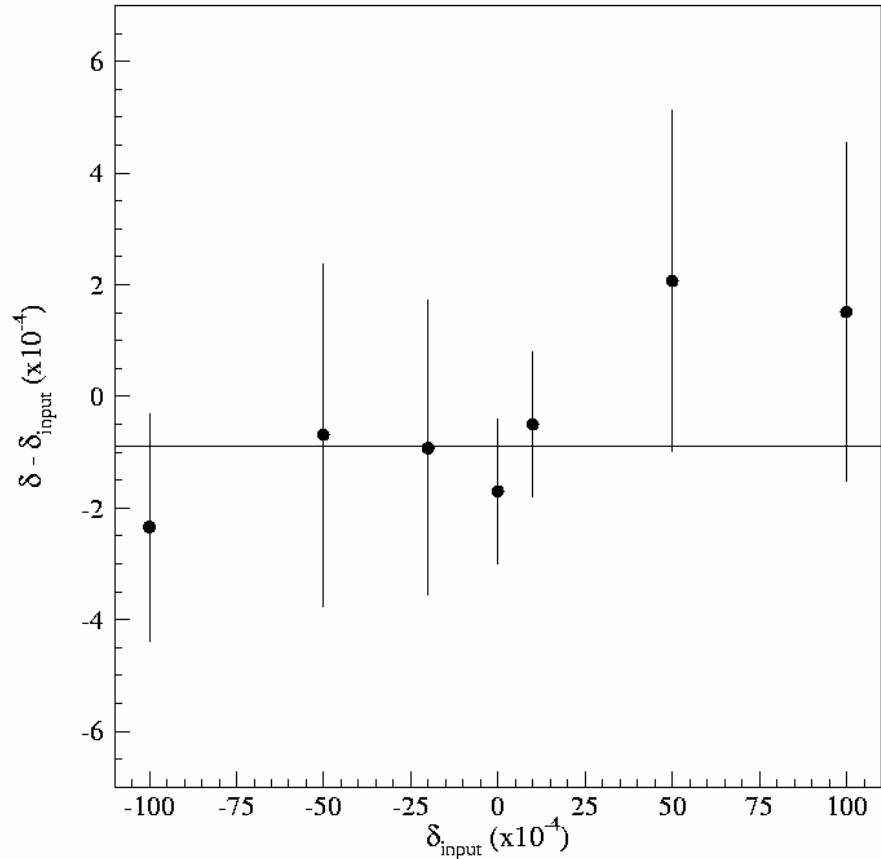
# Weighting Method: Correcting for the Production Difference

- Matched the  $\Xi$  momentum,  $y$  position at the collimator exit, and  $y$  slope at the collimator exit.
- Cut the non-flat regions of the  $x$  position and  $x$  slope distributions at the collimator exit.
- Approach does **not** correct for the acceptance difference due to **spectrometer inefficiencies**.



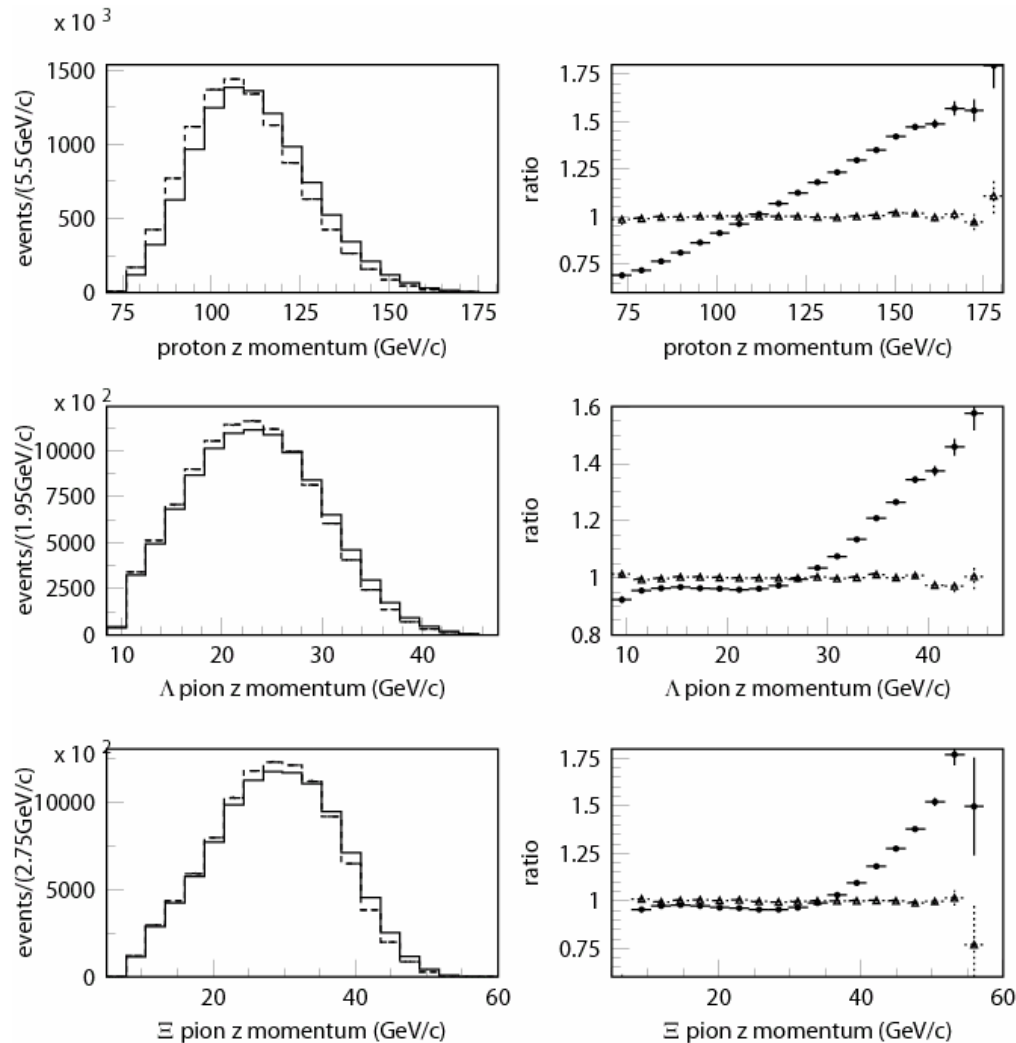
# Monte Carlo

- To reduce processing time, and to improve the simulation, the  $\Xi$  position and momentum at the exit of the collimator was taken from **data, not simulated**. This approach was termed the Collimator Hybrid Monte Carlo (CHMC).
- The rest of the decay sequence was simulated from the collimator exit.
- The **full analysis** was run on each sample.
- The CHMC is only used to verify code and study some systematics, the result is not Monte Carlo dependent.



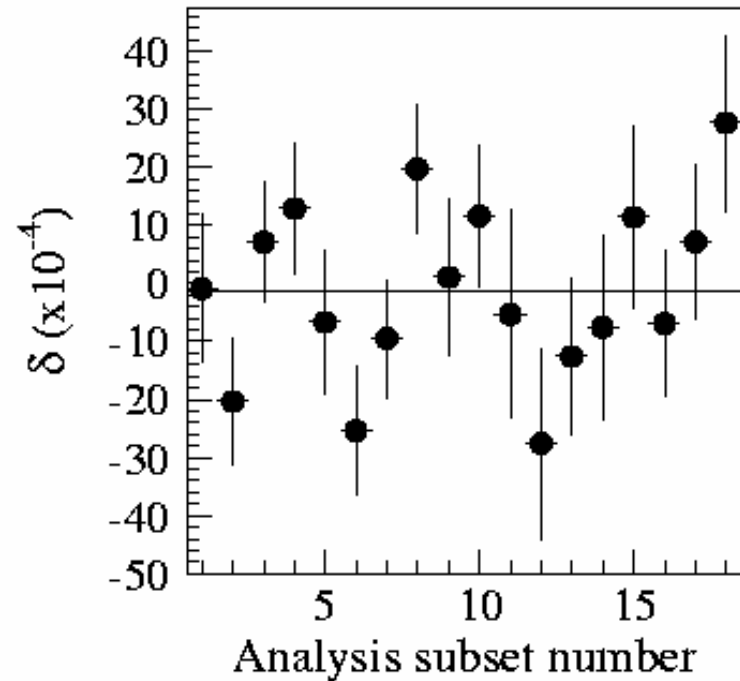
$$\delta = (\alpha_{\Lambda} \alpha_{\Xi})_{-} - (\alpha_{\Lambda} \alpha_{\Xi})_{+}$$

# Correcting Acceptance Differences in Real Data



# $A_{\Xi\Lambda}$ Measurement

- For this analysis data were taken from the **end** of the 1999 run, when the spectrometer was most stable.
- Runs with **high** inefficiencies were **not** included.



$$\delta_{raw} = (-1.3 \pm 3.0) \times 10^{-4}$$

$$A_{\Xi\Lambda} = (0.0 \pm 5.1) \times 10^{-4}$$

$$\delta_{corr.} = (0.0 \pm 3.0) \times 10^{-4}$$

$$\#\Xi^- = 118 \times 10^6$$

$$\chi^2 / ndf = 1.4$$

$$\#\Xi^+ = 42 \times 10^6$$

# Systematic Summary

$x$ position at Collimator cut	$1.2 \times 10^{-4}$
$x$ slope at Collimator cut	$1.4 \times 10^{-4}$
Analysis Magnet	$2.8 \times 10^{-4}$
Hodoscope	$0.3 \times 10^{-4}$
Calorimeter	$2.1 \times 10^{-4}$
Interaction Difference	$0.9 \times 10^{-4}$
Background	$0.3 \times 10^{-4}$
Bin size	$0.4 \times 10^{-4}$
Validation of the Analysis Code	$1.9 \times 10^{-4}$
$\alpha_{\Lambda} \alpha_{\Xi}$ PDG error	$0.3 \times 10^{-5}$
Total	$4.2 \times 10^{-4}$

# Conclusion

- Over  $119 \times 10^6$   $\Xi^-$  and  $42 \times 10^6$   $\bar{\Xi}^+$  (10% of the *HyperCP* data) have been analyzed, using a weighting method, giving a **preliminary** result almost 20 times smaller than the previous best measurement
- The result is consistent with the result from a parallel Hybrid Monte Carlo study done on a different subset of the data.
- A number of systematic errors have been studied. The largest of these are the calorimeter and analysis magnet systematic errors.
- The weighting analysis method will be used to measure the entire *HyperCP* data set further constraining the SUSY models and other exotic forms of *CP* violation.
- The **preliminary** result is :

$$A_{\Xi\Lambda} = [0.0 \pm 5.1(stat.) \pm 4.2(syst.)] \times 10^{-4}$$